U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

HYDROLOGIC INVESTIGATIONS ATLAS HA 725
Ground-water discharge—SHEET 3 OF 3
Eberts, S.M., 1999, Water levels and ground-water discharge, regional aquifer system of the Midwestern Basins and Arches region, in parts of Indiana, Ohio, Illinois, and Michigan

GROUND-WATER DISCHARGE

To understand ground-water flow in an aquifer system in a humid region and to delineate recharge and discharge areas of the aquifer system, the relation between ground and surface waters must be understood. In general, ground water discharges to a stream if the water table is above the stage of the stream, whereas the stream loses water to the aquifers if the water table is below the stream stage. Seasonal fluctuations of ground-water levels in shallow flow systems with large recharge areas contribute to fluctuations in ground-water discharge to streams (base flow) over the course of a year. Under natural conditions, flow in the regional drains and their principal tributary streams throughout the study area increases with distance downstream because ground water discharges to these streams except when water is forced into streambank deposits during floods. Ground-water discharge in Ohio is highest where streams follow outwash deposits or flow across ice-contact stratified drift and is lowest where streams flow across ground-moraine, end-moraine, and lacustrine deposits (Cross, 1949).

Ground-water discharge to streams can be estimated from streamflow data by separating streamflow hydrographs into their direct runoff and base flow components. Such estimates of base flow do not distinguish between discharge from local, intermediate, and regional flow systems within an aquifer system, but they are useful to help quantify a general water budget for the aquifer system. Mean ground-water discharge to streams for the period associated with unregulated or only minimally regulated low flow was computed from such data for selected streamflow-gaging stations within the study area. These values describe the central tendency of ground-water discharge associated with long-term steady-state conditions in the aquifer system, but do not provide information on the adequacy of streamflow for specific uses at specific times.

Because the Midwestern Basins and Arches—RASA project is regional in scope, ground-water flow in shallow, local flow systems could not be fully investigated as part of this study. As a result, estimating discharge to streams from comparatively stable, regional and possibly intermediate flow systems within the aquifer system was also desirable. Estimates of this sustained ground-water discharge component of base flow were computed by further analysis of the base-flow data described above.

DATA ANALYSIS

Daily mean streamflows retrieved from the USGS National Water-Data Storage Retrieval System (WATSTORE) were used to estimate daily mean base flows for selected streamflow-gaging stations. These base flow values were then used to estimate mean ground-water discharge and mean sustained ground-water discharge to the selected stream reaches. Only the record for which low flow was either unregulated or only slightly regulated was used in the analysis of each station. Because long-term steady-state conditions in the aquifer system were to be represented by the estimates of ground-water discharge, the period selected for analysis for each station was required to include wet and dry periods and at least 10 complete water years of record. Wet and dry periods were determined by inspection of departure plots (fig. 7). [Departure plots illustrate departures of the average of the daily mean base flows for each water year (annual mean base flow) from the corresponding average of the annual mean base flows (mean annual base flow).] Specifically, periods of record for stations on regional drains or along streams that drain into a common regional drain within the study area boundary were compared with the wet and dry periods of the station within the group that had the longest period of record and was further downstream than other stations with similar or shorter lengths of record.

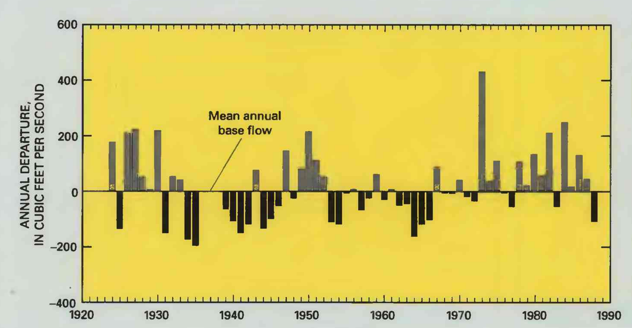


Figure 7. Departures of annual mean base flows from the mean annual base flow for streamflow-gaging station 04198000 on the Sandusky River, Ohio. Bars represent annual mean base flows. Bars above zero-departure line represent wet periods; bars below zero-departure line represent dry periods.

Hydrograph-separation techniques were used to divide streamflow into direct runoff and base flow components. Numerous methods of hydrograph separation are available, and each method results in a slightly different estimate of direct runoff and base flow. A computer program (R.A. Sloto, U.S. Geological Survey, written commun., 1988) was used in this investigation to implement the local-minimum method of hydrograph separation (fig. 8) (Pettyjohn and Henning, 1979). The local-minimum method provides the most conservative (lowest) estimate of daily mean base flows of the three methods described by Pettyjohn and Henning (1979) and was recommended by these authors for use in regional investigations. Mean ground-water discharge to selected stream reaches was estimated by computing the average of all daily mean base flows for the period selected for analysis for each selected streamflow-gaging station.

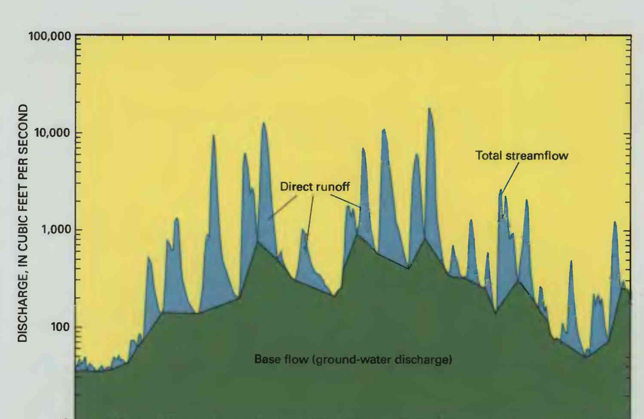


Figure 8. Example of hydrograph separation by the local-minimum method of Pettyjohn and Henning (1979) for the 1969 water year for streamflow-gaging station 04198000 on the Sandusky River, Ohio.

Base-flow-duration curves were constructed from the daily mean base flows for each selected streamflow-gaging station. (Base-flow-duration curves are cumulative frequency curves that show the percentage of time during which specified base flows were equaled or exceeded in a given period.) It was observed that base-flow-duration curves for streamflow-gaging stations along small tributary streams or streams that drain areas underlain by low permeability rock are made up of a single limb (fig. 9A), whereas base-flow-duration curves constructed for streamflow-gaging stations along regional drains or their principal tributary streams are made up of two limbs (fig. 9B). The lower limb of such curves, which is the missing limb on the single limb curves, commonly plots as a straight line on log-probability paper and represents a flattening of the overall curve. The two limbs on these curves suggest the presence of at least two sources of ground-water inflow to the regional drains and their principal tributary streams.

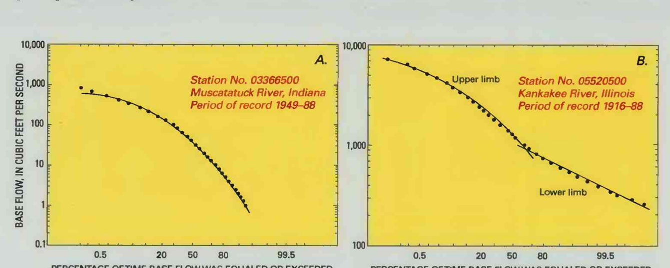


Figure 9. Example of base-flow-duration curves for (*A*) small tributary streams or streams that drain areas underlain by low permeability rock and (*B*) large regional drains or principal tributary streams.

Superimposed base-flow-duration curves for a single streamflow-gaging station, constructed from periods of record that represent different ground-water recharge conditions, provide insight into the sources of ground-water inflow that result in the upper and lower limbs of the curves for the regional drains and their principal tributary streams. The superimposed curves show that daily mean base flows that make up the upper limbs of the curves are, in large part, from a source of ground-water inflow that readily responds to variations in ground-water recharge from precipitation (fig. 10). This is evident from the differences in the upper limbs of curves constructed from the entire period of record; from only summer months, when potential evapotranspiration exceeds precipitation (Todd, 1969); and from a period of drought (U.S. Geological Survey, 1991). The daily mean base flows that make up the lower limbs of the curves are from a source of ground-water inflow not greatly affected by variations in ground-water recharge from precipitation, as evident from the minimal differences between the lower limbs of the curves constructed for the different ground-water recharge conditions (fig. 10).

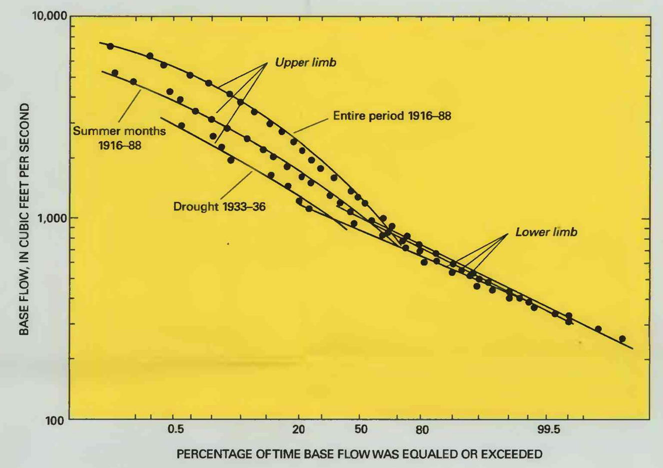


Figure 10. Base-flow-duration curves for streamflow-gaging station 05520500 on the Kankakee River, Ill. constructed from periods of record that represent different ground-water recharge conditions.

The population of daily mean base flows associated with the upper limbs seems to consist of an appreciable amount of discharge from local ground-water-flow systems in addition to discharge from intermediate and regional ground-water-flow systems. This is because ground-water levels in local ground-water-flow systems readily decline in the summer and during droughts in response to a decrease in recharge from precipitation; this decline results in a substantial decrease in discharge to streams from the local ground-water-flow systems. The population of daily mean base flows associated with the lower limbs of the base-flow duration curves consists of the lowest daily mean base flows and is less variable than the population associated with the upper limbs. This population seems to be more dominated by discharge from regional and possibly intermediate ground-water-flow systems than the population associated with the upper limbs.

Mean sustained ground-water discharge to the selected stream reaches was estimated by computing the average of all daily mean base flows that contribute to the lower limb of the base-flow-duration curve for the period selected for analysis for each streamflow-gaging station. The base-flow-duration curves were constructed using the method described by Searcy (1959), except that daily mean base flows were used instead of daily mean streamflows. The base-flow-duration curves were constructed with the aid of a computer program developed by Lumb and others (1990).

Although different methods of hydrograph separation resulted in slightly different estimates of daily mean base flows, estimates of mean sustained ground-water discharge computed from the estimates of base flow did not differ. This is probably because hydrograph-separation techniques differ most in the way they separate direct runoff and base flow during high streamflows and daily mean base flows that are associated with sustained ground-water discharge are from periods of low streamflow.

ESTIMATED GROUND-WATER DISCHARGES FOR LONG-TERM STEADY-STATE CONDITIONS

Mean ground-water discharge for selected streamflow-gaging stations is shown in figure 11. These values approximate the central tendency of ground-water discharge to the selected stream reaches from a combination of local, intermediate, and regional ground-water-flow systems. Each value represents the entire drainage basin above the corresponding station. Corresponding station numbers, station names, periods analyzed, and contributing drainage areas are listed in table 1.

Table 1. Gaging stations for which streamflow and ground-water discharge statistics were estimated

[mi^2, square miles; two-digit numbers after basin names refer to hydrologic unit codes in figure 11]

Station number	Station name	Period analyzed (water years)	Drainage area (mi^2)
	OHIO RIVER BASIN (03)		
Scioto River Basin			
03219500	Scioto River near Prospect, Ohio	1926–32; 1940–91	567
03229500	Big Walnut Creek at Rees, Ohio	1922–35; 1940–55	544
03230000	Scioto River near Circleville, Ohio	1940–51	2,635*
03230500	Big Darby Creek at Darbyville, Ohio	1922–35; 1939–88	534
03231000	Deer Creek at Williamsport, Ohio	1927–35; 1939–56	333
03231500	Scioto River at Chillicothe, Ohio	1922–88	3,849*
03234000	Paint Creek near Bourneville, Ohio	1924–36; 1940–51	807*
03234500	Scioto River at Higby, Ohio	1930–86	5,131*
03237500	Ohio Brush Creek near West Union, Ohio	1927–35; 1941–88	387
Little Miami River Basin			
03242500	Little Miami River near Fort Ancient, Ohio	1940–51	677
03247050	East Fork Little Miami River near Batavia, Ohio	1966–76	352
Great Miami River Basin			
03261500	Great Miami River at Sidney, Ohio	1915–88	541*
03262700	Great Miami River at Troy, Ohio	1963–88	926*
03263000	Great Miami River at Taylorsville, Ohio	1923–88	1,149*
03265000	Stillwater River at Pleasant Hill, Ohio	1917–28; 1936–88	503
03266000	Stillwater River at Englewood, Ohio	1927–88	650
03270000	Mad River near Dayton, Ohio	1916–21; 1925–73	635*
03272000	Twin Creek near Germantown, Ohio	1915–23; 1928–88	275*
03274000	Great Miami River at Hamilton, Ohio	1932–88	3,630*
03275000	Whitewater River near Alpine, Ind.	1929–88	522
03276500	Whitewater River at Brookville, Ind.	1924–73	1,224
Wabash River Basin			
03323000	Wabash River at Bluffton, Ind.	1931–71	532*
03324500	Salomonie River at Dora, Ind.	1925–64	557
03325000	Wabash River at Wabash, Ind.	1924–34; 1936–64	1,768
03327000	Mississinewa River at Peoria, Ind.	1953–63	808
03328500	Eel River near Logansport, Ind.	1944–88	789
03329500	Wabash River at Delphi, Ind.	1941–64	4,072
03331500	Tippecanoe River near Ora, Ind.	1944–90	856
03335000	Wildcat Creek near Lafayette, Ind.	1955–88	794
03335500	Wabash River at Lafayette, Ind.	1924–64	7,267*
03348500	White River near Noblesville, Ind.	1916–26; 1929–74	828*
03351000	White River near Nora, Ind.	1930–55	1,219*
03351500	Fall Creek near Fortville, Ind.	1942–88	169
03361500	Big Blue River at Shelbyville, Ind.	1944–88	421
03363000	Driftwood River near Edinburgh, Ind.	1942–88	1,060
03363500	Flatrock River at St. Paul, Ind.	1931–88	303*
03364000	East Fork White River at Columbus, Ind.	1949–88	1,707
03365500	East Fork White River at Seymour, Ind.	1928–89	2,341
	ST. LAWRENCE RIVER BASIN (04)		
Streams tributary to Lake Erie			
04178000	St. Joseph River near Newville, Ind.	1948–91	610
04182000	St. Marys River near Fort Wayne, Ind.	1932–33; 1935–88	762*
04183500	Maumee River at Antwerp, Ohio	1922–35; 1940–81	2,129*
04185000	Tiffin River at Stryker, Ohio	1922–28; 1941–73	410
04186500	Auglaize River near Fort Jennings, Ohio	1922–35; 1941–70	332*
04189000	Blanchard River near Findlay, Ohio	1924–35; 1941–70	346
04192500	Maumee River near Defiance, Ohio	1964–74; 1979–85	5,545*
04193500	Maumee River at Waterville, Ohio	1940–88	6,330
04195500	Portage River at Woodville, Ohio	1929–35; 1940–45	433
04197000	Sandusky River near Mexico, Ohio	1924–35; 1939–82	774
04198000	Sandusky River near Fremont, Ohio	1924–35; 1939–89	1,251
	UPPER MISSISSIPPI RIVER BASIN (05)		
Illinois River Basin			
05517000	Yellow River at Knox, Ind.	1943–77	435
05518000	Kankakee River at Shelby, Ind.	1924–90	1,779
05520500	Kankakee River at Momence, Ill.	1916–88	2,340
05526000	Iroquois River near Chesbanse, Ill.	1924–88	2,120

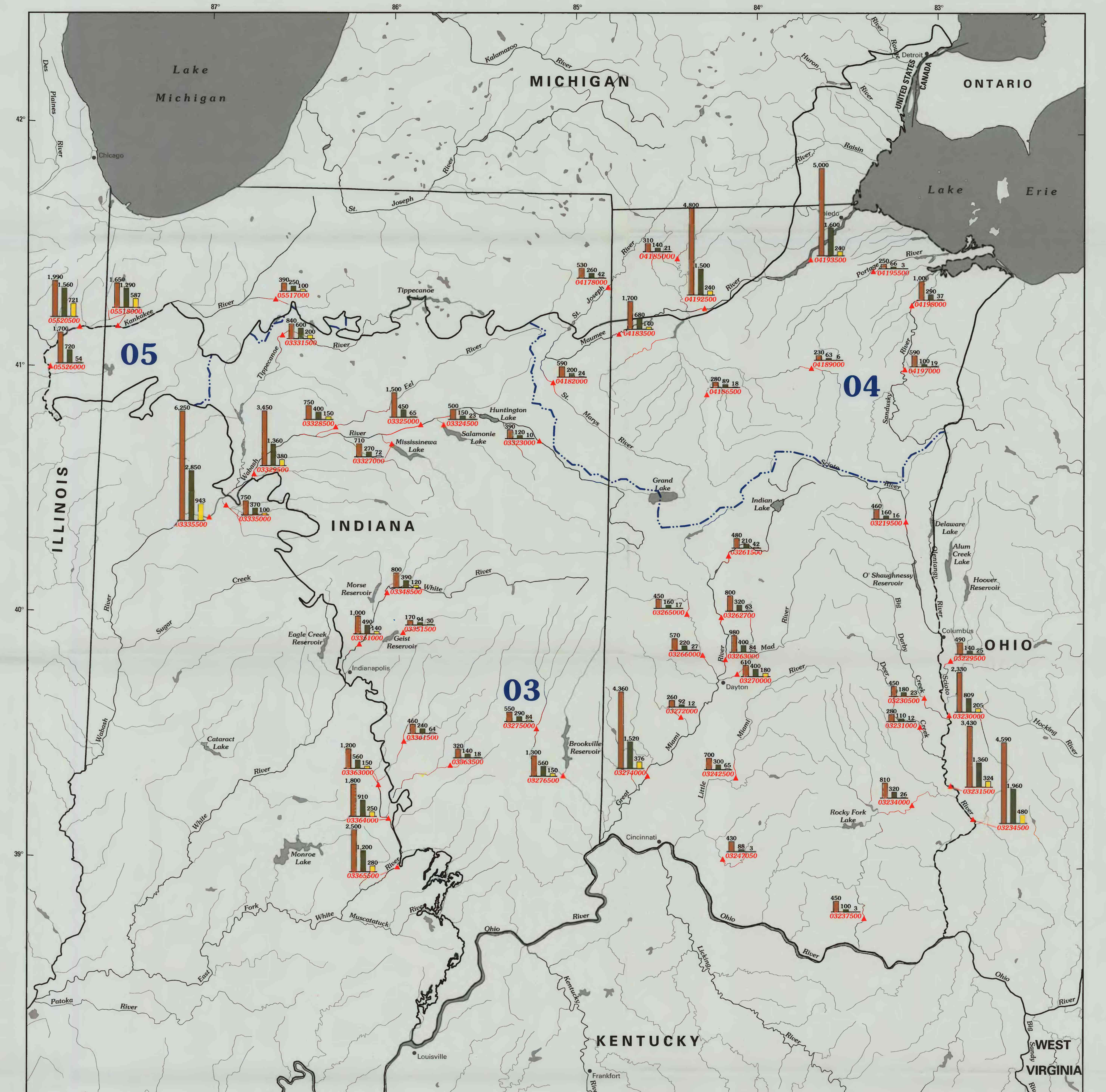
* Low flow slightly regulated during period analyzed.

Mean sustained ground-water discharge for the streamflow-gaging stations is also shown in figure 11. These values approximate the central tendency of the relatively stable component of ground-water discharge to the selected stream reaches, which is predominantly from regional and possibly intermediate ground-water flow systems. The values represent the entire drainage basin above the corresponding stations.

Mean sustained ground-water discharge ranges from 3 to 46 percent of mean ground-water discharge for the selected streamflow-gaging stations for long-term steady-state conditions. These percentages represent ground-water discharge throughout the entire drainage basin above each streamflow-gaging station. Streams that correspond to the highest sustained ground-water discharge as a percentage of ground-water discharge are the Kankakee River in Indiana and Illinois and the Mad River in Ohio. Mean stream discharge, which may be affected by regulation of flow, is presented in figure 11 for each streamflow-gaging station as a frame of reference for the above ground-water-discharge data.

REFERENCES CITED

Anderson, M.P., and Woessner, W.W., 1992, Applied groundwater modeling—Simulation of flow and advective transport: San Diego, Academic Press, p. 229.
Bennison, A.P., comp., 1978, Geological highway map of the Great Lakes Region: American Association of Petroleum Geologists, United States Geological Highway Map Series, Map 11.
Bownocker, J.A., comp., 1920, Geologic map of Ohio: Ohio Geological Survey, reprint 1981, scale 1:500,000.
Bugliosi, E.F., 1990, Plan of study for the Ohio-Indiana carbonate-bedrock and glacial-aquifer system: U.S. Geological Survey Open-File Report 90-151, 26 p.
_____1999, The Midwestern Basins and Arches regional aquifer system in parts of Indiana, Ohio, Michigan, and Illinois—Summary: U.S. Geological Survey Professional Paper 1423-A, 46 p.
Burger, A.M., Forsyth, J.L., Nicoll, R.S., and Wayne, W.J., 1971, Geologic map of the Muncie quadrangle, Indiana and Ohio, showing bedrock and unconsolidated deposits: Indiana Geological Survey Regional Geologic Map 5, Muncie Sheet Part A, scale 1:250,000.
Casey, G.D., 1992, Hydrogeology of the basal confining unit of the carbonate aquifer system in the midwestern basins and arches region of Indiana, Ohio, Michigan, and Illinois: U.S. Geological Survey Open-File Report 92-489, 2 sheets, scale 1:1,000,000.
Changnon, S.A., and Dennison, Jean, 1990, Weather and climate impacts in the midwest during July 1990: Champaign, Ill., Midwestern Climate Center, 3 p.
Clark, G.D., ed., 1980, The Indiana water resource—Availability, uses, and needs: Indianapolis, Governor's Water Resources Study Commission, Indiana Department of Natural Resources, 508 p.
Cross, W.P., 1949, The relation of geology to dry-weather stream flow in Ohio: Transactions of the American Geophysical Union, v. 30, no. 4, p. 563-566.
Flint, R.F., committee chairman, 1959, Glacial map of the United States east of the Rocky Mountains: Boulder, Colo., Geological Society of America, scale 1:1,750,000.
Glatfelter, D.R., Thompson, R.E., Jr., and Nell, G.E., 1989, Water resources data, Indiana, water year 1988: U.S. Geological Survey Water-Data Report IN-88-1, p. 313.
Gray, H.H., 1983, Map of Indiana showing thickness of unconsolidated deposits: Indiana Geological Survey, Miscellaneous Map 37, scale 1:500,000.
Gray, H.H., Droste, J.B., Patton, J.B., Rexroad, C.B., and Shaver, R.H., 1985, Correlation chart showing Paleozoic stratigraphic units of Indiana: Indiana Department of Natural Resources, Geological Survey Supplement to Miscellaneous Map 48.
Gray, H.H., Ault, C.H., Keller, S.J., 1987, Bedrock geologic map of Indiana: Indiana Geological Survey Miscellaneous Map 48, scale 1:500,000.
Gray, H.H., Forsyth, J.L., Schneider, A.F., and Gooding, A.M., 1972, Geologic map of the Cincinnati quadrangle, Indiana and Ohio, showing bedrock and unconsolidated deposits: Indiana Geological Survey Regional Geologic Map 7, Cincinnati Sheet Part A, scale 1:250,000.
Ground Water Subcommittee of the Federal Interagency Advisory Committee on Water Data, 1989, Federal glossary of selected terms—Subsurface water flow and solute transport: U.S. Geological Survey, p. 21.
Hull, D.N., 1990, Generalized column of bedrock units in Ohio: Ohio Department of Natural Resources, Geological Survey, 1 p.
Indiana Department of Natural Resources, 1988, Water resource availability in the Whitewater River basin, Indiana: Water Resource Assessment 88-2, 126 p., 3 pls. in pocket.
_____1990, Water resource availability in the Kankakee River basin, Indiana: Water Resource Assessment, 90-3, 247 p., 2 pls. in pocket.
Johnson, G.H., and Keller, S.J., 1972, Geologic map of the Fort Wayne quadrangle, Indiana, Michigan, and Ohio, showing bedrock and unconsolidated deposits: Indiana Geological Survey Regional Geologic Map 8, Fort Wayne Sheet Part A, scale 1:500,000.
Langbein, W.B., and Iseri, K.T., 1960, General surface-water techniques—general introduction and hydrologic definitions, pt. 1 of manual of hydrology: U.S. Geological Survey Water-Supply Paper 1541-A, p. 7.
Larson, G.E., 1991, Development of Silurian and Devonian lithostratigraphic nomenclature, central-western and northwestern Ohio: Ohio Department of Natural Resources, Geological Survey Open-File Report 91-1, 1 pl.
Lumb, A.M., Kittle, J.L., Jr., and Flynn, K.M., 1990, Users manual for ANNIE, a computer program for interactive hydrologic analysis and data management: U.S. Geological Survey Water-Resources Investigations Report 89-4080, 236 p.
Norris, S.E., Cross, W.P., and Goldthwait, R.P., 1950, The water resources of Greene County, Ohio: Ohio Department of Natural Resources, Division of Water Bulletin 19, p. 23.
Norris, S.E., and Fidler, R.E., 1973, Availability of water from limestone and dolomite aquifers in southwest Ohio and the relation of water quality to the regional flow system: U.S. Geological Survey Water-Resources Investigations 17-73, 42 p.
Pettyjohn, W.A., and Henning, R.J., 1979, Preliminary estimate of ground-water recharge rates, related streamflow and water quality in Ohio: Columbus, Ohio State University, Water Resources Center, Project Completion Report 553, 323 p.
Rupp, J.A., 1991, Structure and isopach maps of the paleozoic rocks of Indiana: Indiana Geological Survey Special Report 48, p. 40, 48.
Rupp, J.A., and Pennington, Dean, 1987, Determination of the 10,000 mg/l TDS surface within the bedrock aquifers of Indiana: Indianapolis, Indiana Academy of Science, [Proceedings], 1987, v. 97, p. 383-389.
Scott, J.C., 1991, Computer software for converting ground-water and water-quality data from the National Water Information System for use in a geographic information system: U.S. Geological Survey Water-Resources Investigations Report 90-4200, 55 p.
Searcy, J.K., 1959, Flow-duration curves: U.S. Geological Survey Water-Supply Paper 1542-A, 33 p.
Shaver, R.H., regional coordinator, 1985, Midwestern basin and arches region—Correlation of stratigraphic units of North America (COSUNA) project: American Association of Petroleum Geologists, 1 sheet.
Shindel, H.L., Klingler, J.H., Mangus, J.P., and Trimble, L.E., 1991a, Water resources data, Ohio, water year 1990: U.S. Geological Survey Water-Data Report OH-90-1, v. 1, 305 p.
_____1991b, Water resources data, Ohio, water year 1990: U.S. Geological Survey Water-Data Report OH-90-2, v. 2, 281 p.
Soller, D.R., 1986, Preliminary map showing the thickness of glacial deposits in Ohio: U.S. Geological Survey Miscellaneous Field Studies Map 1862, scale 1:500,000.
Stewart, J.S., and Nell, G.E., 1991, Water resources data, Indiana, water year 1990: U.S. Geological Survey Water-Data Report IN-90-1, 340 p.
Strobel, M.L., 1990, Characteristics affecting the vertical flow of ground water through selected glacial deposits in Ohio: Columbus, Ohio State University, Master's thesis, 185 p.
Sun, R.J., 1986, Regional aquifer-system analysis program of the U.S. Geological Survey, Summary of projects, 1978-84: U.S. Geological Survey Circular 1002, 264 p.
Todd, D.K., 1969, Ground water resources of the Upper Great Miami River basin and the feasibility of their use for streamflow augmentation: Dayton, Ohio, Miami Conservancy District, 142 p.
_____1980, Groundwater hydrology (2d ed.): New York, Wiley, p. 225.
Toth, Jozsef, 1963, A theoretical analysis of groundwater flow in small drainage basins: Journal of Geophysical Research, v. 68, no. 16, p. 4795-4812.
U.S. Environmental Protection Agency, 1984, National secondary drinking water regulations: U.S. Environmental Protection Agency, EPA-570/9-76-000, Appendix A.
U.S. Geological Survey, 1973, Indiana base map: Reston, Va., scale 1:500,000.
_____1977, Ohio base map: Reston, Va., scale 1:500,000.
_____1991, National water summary 1988-89—Hydrologic events and floods and droughts: United States Geological Survey Water-Supply Paper 2375, p. 271-278; 443-450.
_____1999, National Atlas of the United States, Hydrologic Units map: Reston, Va., scale 1:3,500,000.
Willman, H.B., and others, comps., 1967, Geologic map of Illinois: Illinois State Geological Survey, scale 1:500,000.



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972

0 10 20 30 40 50 60 MILES
0 10 20 30 40 50 60 KILOMETERS

Basin boundaries from The National Atlas of the United States, Hydrologic Units map, 1:3,500,000, 1998

EXPLANATION

04 **Boundary of major river basin**—Number indicates basin; 03, Ohio River Basin; 04, St. Lawrence River Basin; 05, Upper Mississippi River Basin

Study-area boundary—Solid where coincident with contact between Devonian limestones and younger Devonian shales. Dashed where coincident with surface-water body

1,300 — Mean stream discharge
560 — Mean ground-water discharge
150 — Mean sustained ground-water discharge
03276500 — Station number

Streamflow gaging station—Discharge, in cubic feet per second. (Some stream-discharge numbers reflect slight regulation of flow. Some ground-water discharge numbers reflect slight regulation of low flow, as indicated in table 1)

Figure 11. Mean stream discharge, mean ground-water discharge, and mean sustained ground-water discharge at selected streamflow-gaging stations for long-term steady-state conditions in the glacial-deposit and carbonate-bedrock aquifer system.

WATER LEVELS AND GROUND-WATER DISCHARGE, REGIONAL AQUIFER SYSTEM OF THE MIDWESTERN BASINS AND ARCHES REGION, IN PARTS OF INDIANA, OHIO, ILLINOIS, AND MICHIGAN

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1999

INTERIOR—GEOLOGICAL SURVEY, RESTON, VIRGINIA—1999